CEMENT AND LIME MANUFACTURE

VOL. XV. No. 1 JANUARY 1942 PRICE 1/- MONTHLY

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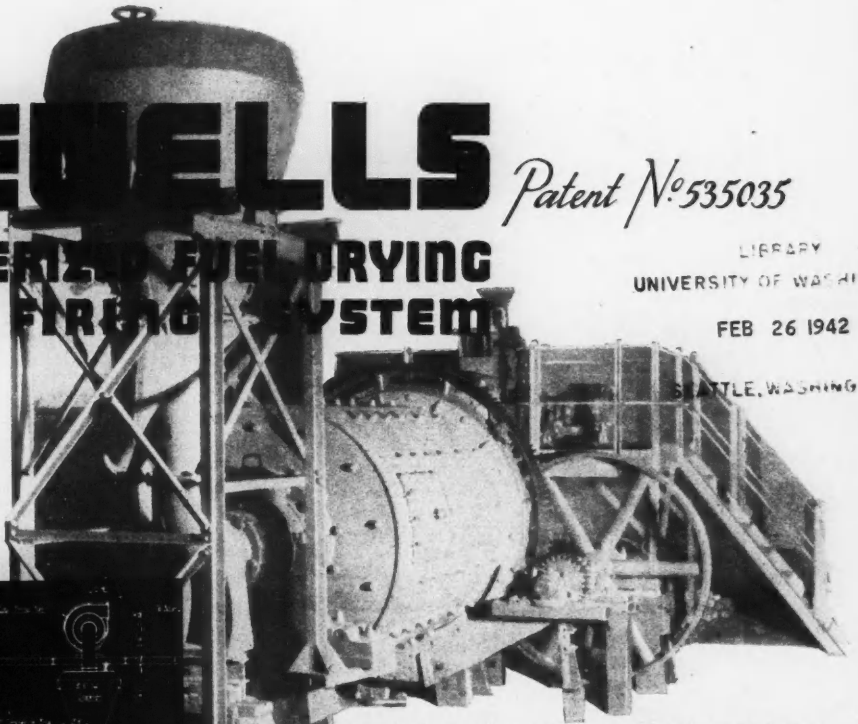

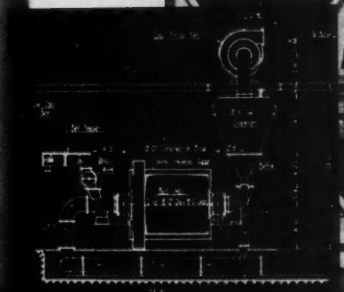

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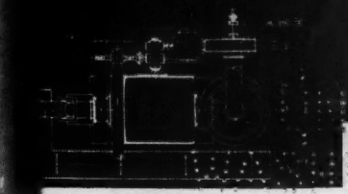

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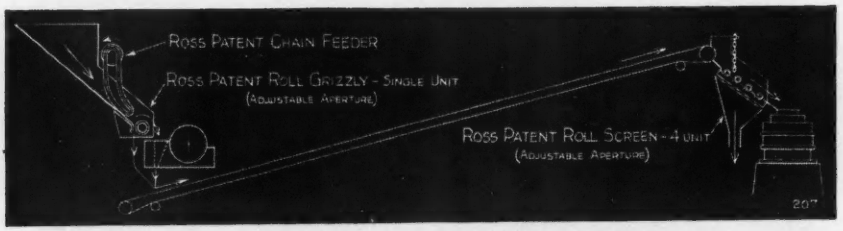

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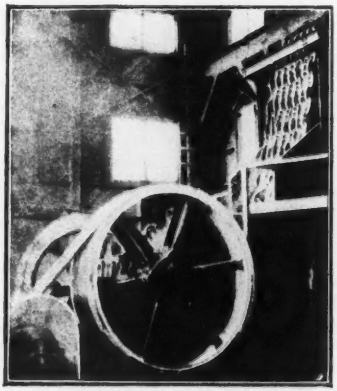

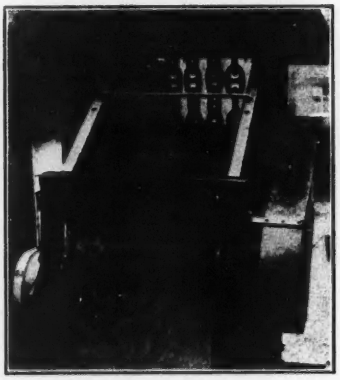

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Effect on Clinker of Heat Treatment and Rate of Cooling.

A REPORT of the United States National Bureau of Standards, known as Research Paper No. 1358, discusses the effect of heat treatment and the rate of cooling upon the microscopic structure of Portland cement. The author, Mr. G. W. Ward, points out that in recent years successful attempts have been made to vary the relative proportions of the constituents by changing the rate of cooling of the clinker. Correlations between calculated clinker compositions assuming complete crystallisation and the physical properties of the resulting cements have not been precise.

In the investigations described in the report, ten samples were taken from a series of 26 commercial clinkers which covered the range of compositions found in commercial practice. One portion of each clinker (designated as *P*) was examined in its original condition. A second portion of each clinker was reheated in an experimental rotary kiln (5 in. by 8 ft.) at a temperature of 1,400 deg. to 1,425 deg. C. (2,552 deg. to 2,597 deg. F.) and cooled to 1,250 deg. C. (2,282 deg. F.) in two to three minutes in order to yield a maximum amount of glass. This quickly-cooled clinker was designated *Q*. A third portion was reheated to the same temperature in a laboratory batch kiln and cooled to 1,250 deg. C. (2,282 deg. F.) at a uniform rate in about three hours in order to yield a minimum of glass. This slowly-cooled clinker was designated *S*. The heating and cooling were carried out under oxidising conditions. The ten random clinkers with their variously heat-treated counterparts gave thirty samples for study.

The clinkers were studied microscopically and were analysed chemically. The investigation with the microscope included examination of powders, thin and polished thin sections, together with variously etched polished specimens. Quantitative measurements were made, using etched and polished specimens

mounted in Bakelite resin. When ready for examination the surface of each specimen contained from 15 to 20 clinker particles. All quantitative measurements were made with a Wentworth micrometer attached to the microscope stage. Each value reported was the average of five equally-spaced traverses on each of five mounts. The etchants proposed by Tavasci and Insley, with modifications in some instances, were found to be generally satisfactory. Glass was determined microscopically after a water etch followed by 1 per cent. nitric acid-alcohol solution, and after an etch by 10 per cent. potassium hydroxide in water.

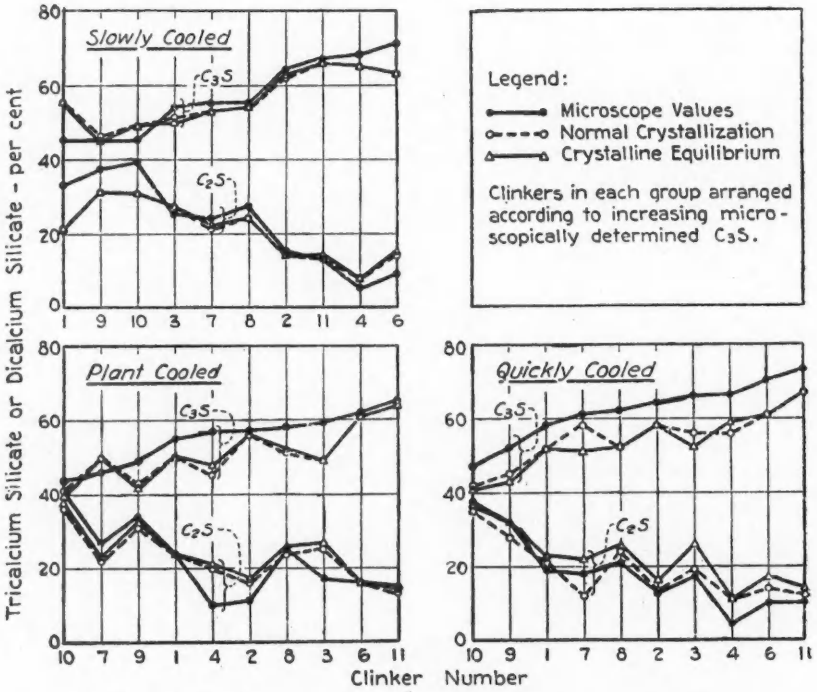

Fig. 1. Comparisons of Tricalcium Silicate and Dicalcium Silicate.

The results of the examination of the samples and of their slowly- and quickly-cooled counterparts are reported. These are compared with the quantitative phase composition obtained from chemical analyses by two methods of calculation to show the deviation to be expected among the different methods. The general appearance of each phase in the clinker is described together with the changes due to differences which had occurred in heat treatment and cooling rate.

It is shown that there is a definite trend toward simplicity of crystal form and clinker structure as the cooling rate increases. Clinkers cooled in the plant

have structures that indicate that their rate of cooling lies intermediate between slow and quick cooling.

Comparisons between calculations of phases from microscopical observations and from chemical analyses, according to the presence or absence of glass, show that:

(1) The agreement between phases calculated under the assumption of complete equilibrium crystallisation and by the microscopical method is better for the slowly-cooled clinkers than for either the plant-cooled or quickly-cooled clinkers.

(2) In general, for all clinkers, the phase compositions calculated with consideration of glass (normal crystallisation) agreed better with the microscopically determined phases than did calculations in which complete equilibrium crystallisation was assumed.

(3) The $3CaO.SiO_2$ found microscopically nearly always exceeded that calculated by either of the other methods.

(4) The $2CaO.SiO_2$ microscopically determined was sometimes greater and at other times less than that calculated to be present by either method irrespective of Al_2O_3-Fe_2O_3 ratios.

(5) The microscopically-determined $3CaO.Al_2O_3$ was always less than that calculated by either of the other methods.

(6) The total dark interstitial phases—rectangular, prismatic, and glass—determined microscopically approached the total tricalcium aluminate calculated on the assumption of crystalline equilibrium.

(7) The $4CaO.Al_2O_3.Fe_2O_3$ determined microscopically in general exceeded that calculated by either of the other methods and showed better agreement for high Al_2O_3-Fe_2O_3 ratios than for low.

(8) The glass determined microscopically was in better agreement with values obtained from the heat-of-solution method for slowly-cooled and plant-cooled clinkers than for quickly-cooled clinkers.

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Effect of the Addition of Organic Materials to Cement.*

THE results of investigations extending over seven years on the effect of the addition of various organic materials to cement have been described by Mr. M. A. Swayze, director of research of the Lone Star Cement Corporation of America. The three classes of materials studied were: (1) mineral oils; (2) animal or vegetable fats or oils; and (3) natural resins. The effects of these substances on concrete strength, volume change, percentage of air voids, and durability are shown in the tables.

Mineral Oils.

A mineral oil admixture may enter the cement through leakage of bearings in some types of grinding machinery. In former years complete grinding of cement in these mills introduced as much as 0·05 to 0·10 per cent. of oil into cement, but recently this has materially decreased or entirely stopped. Tests of cement ground with 0·03 per cent. of crusher oil showed that the oil had little effect on either workability or strength. Air voids were only slightly increased. Durability in freezing and thawing was increased by the oil addition.

Animal or Vegetable Fats.

Additions of animal or vegetable fats or oils have been made to Portland cement for many years for obtaining "waterproof" products, or for increasing resistance to setting when long periods of storage are contemplated. Several tests have been made on cements containing 0·03 per cent. of beef tallow. *Table* I gives a typical comparison of the effect on concrete properties. All data are averages of three tests.

The increase in air content induced by the tallow increased yield and caused a reduction in the quantity of cement per cubic yard. Therefore greater reductions in strengths of the tallow concrete were obtained than would have resulted if the comparison had been on the basis of equal cement contents. It is noteworthy that in the lean mixes little loss in strength results from the admixture. Richer mixes generally have far more strength than is used in concrete design, and the greater decrease in strength due to admixtures in this range seems relatively unimportant. The effect of tallow on the air content of concrete is variable. Increase in voids is greater as cement content is lowered; voids also increase with higher slumps. Shrinkage of concrete in air is increased by tallow additions. The average increase amounts to 13 per cent. Similar increases in the shrinkage of concrete have been found in other tests.

The greatest effect of tallow or resin additions to cement is on resistance to freezing and thawing. While the durability of all mixes is increased, the effect is greatest in the lean mixes and least for the 7·5 sack batches, which by their low water content are normally of high resistance even with untreated cements. A very significant difference is notable in the type of disintegration obtained.

* It is important to note the optimum amounts of oils and resins given in this article. More than these amounts causes serious loss of strength, and is definitely dangerous.

Normally, frost attack is always at the top surface of concrete, showing as a scaling of the finished surface. As the number of freezing cycles mounts this scaling progresses downward, with real disintegration generally confined to the top half of the test specimen. Both resin and tallow additions to cement prevent this differential action. Scaling or disintegration of concrete containing these materials takes place much more slowly, and the frost attack is uniformly distributed over all surfaces of test specimens. This difference is of importance in weathering of exposed concrete. Many engineers have stated that more durable concrete roads would be obtained if the slabs after curing could be turned over. It now appears possible to attain the same result with treated cements.

TABLE I.—COMPARISON OF CEMENTS WITH AND WITHOUT THE ADDITION OF TALLOW.
(Strengths in lb. per sq. in.).

Sacks Cu.yd.	Net W/C	Flow %	Slump In.	Wgt. Cu.yd.	Voids %	Strength, 1 Da	3 Da	7 Da	28 Da	3 Mo	1 Yr
2" Slump Concrete, Moist Curing Cement "E"—No Admixture											
3.46	9.75	164	1.7	145.3	3.1	270	830	1470	2120	2390	2280
4.24	7.57	163	2.0	146.7	3.7	460	1470	2320	3470	3620	3900
5.02	6.05	157	2.0	148.8	3.1	730	2350	3480	4800	4980	5270
6.01	5.05	156	2.1	150.8	2.3	1110	3300	4530	5780	6120	6240
7.54	4.22	154	2.4	151.7	1.8	1640	3960	5380	6260	6990	7520
Cement "E_1"—0.030% Beef Tallow											
3.32	8.18	159	1.9	137.8	10.1	260	930	1530	2040	2440	2280
4.10	6.41	153	2.0	140.4	9.2	420	1490	2500	3210	3670	3460
4.81	5.64	160	2.2	141.9	8.3	560	1900	2960	3970	4200	4250
5.76	4.96	157	2.3	144.2	6.6	740	2530	3710	4720	4900	5330
7.11	4.36	161	2.2	146.0	5.1	960	2880	4280	4600	5440	5740
6" Slump Concrete—Moist Curing Cement "E"—No Admixture											
3.42	10.66	194	5.3	144.3	3.4	220	810	1190	1900	2140	2070
4.21	8.25	203	6.2	146.4	2.9	350	1240	1940	3160	3050	2760
4.94	6.82	205	6.3	147.8	2.8	540	1940	2960	3940	4370	4600
5.94	5.40	184	6.0	149.7	2.3	940	2950	4040	5610	5550	6600
7.40	4.61	183	6.2	149.9	2.0	1250	3480	4750	6270	6240	7330
Cement "E_1"—0.030% Beef Tallow											
3.23	8.62	177	5.9	134.5	11.9	200	750	1180	1910	2040	1800
3.90	7.00	192	6.2	135.7	11.5	310	1120	1760	2630	2690	2660
4.65	5.95	191	6.0	137.6	10.6	390	1450	2200	3110	3220	3280
5.54	5.18	189	6.0	139.1	9.5	500	1760	2650	3510	3650	3850
6.95	4.69	193	6.0	140.7	8.0	640	2150	3040	3940	4380	4630

Natural Resins.

When gum or wood resins are added in amounts from 0·01 to 0·05 per cent. the effects are striking, as shown in *Table* II. Vinsol resin is a product extracted from pine wood, but similar results have been obtained with ordinary resin. The concrete was designed according to a State highway specification, with water variable to produce the desired slump. This procedure gave a reduction in cement content of 1½ to 4 per cent., depending on the quantity of resin present. Strength reductions due to increased air content ranged from 5 to 20 per cent., and were less than those found for similar tallow additions. Volume change of concrete was not affected by any of the quantities of resin represented. Resistance to freezing and thawing was markedly increased by the first 0·01 per cent.

increment of resin addition. Further increases in durability resulted with additional increments, but the change was not so great.

A further effect of resin or tallow additions is their effect on workability of concrete. Although slump and flow figures in the data were nearly identical, a decided increase in plastic properties was noted even with as little as 0·01 per cent. of these materials present. Mixes are easier to deform under pressure, placing is easier, and the cement paste holds more firmly to the aggregates, with little or no segregation of water on standing. All these effects are obtained by the first 0.01 per cent. of addition ; further increases had a smaller increment of effectiveness.

Table III shows a comparison of a normal Portland cement with one of identical composition but containing 0·02 per cent. Vinsol resin. The treated cement was considerably coarser than the normal product. Concrete batches were the same as those in *Table* I. The effect of the resin on the air content of the concrete, as in the case of tallow treatment, is variable, lean or wet mixes being affected more than richer or stiffer batches. Concrete shrinkage in air at 50-per-cent.

TABLE II.—EFFECT ON CONCRETE OF THE ADDITION OF VINSOL RESIN TO CEMENT.
(Strengths in lb. per sq. in.).

RESIN %	WATER GAL/ SACK	SACKS PER CU.YD.	WT. PER CU.FT.	% AIR VOIDS	SLUMP IN.	FLOW %	STRENGTHS					
							1 DA	3 DA	7 DA	28 DA	3 MO	1 YR
None	5.41	6.12	149.0	2.4	2.5	169	1100	2860	4090	5540	6220	6600
.01	5.29	6.04	146.6	4.2	2.5	164	1000	2730	3870	5230	5780	6200
.02	5.12	5.99	145.2	5.1	2.5	163	950	2700	3750	4990	5640	6170
.03	5.11	5.85	141.8	7.7	3.2	175	930	2380	3740	4430	5090	5160
.04	5.01	5.89	142.3	7.5	2.5	165	760	2500	3720	4670	5290	5340
.05	4.95	5.88	142.0	7.9	2.5	165	670	2430	3750	4780	5270	5440

relative humidity is not appreciably affected by the admixture. Durability is greatly promoted by the small quantity of resin, especially in the leaner types of concrete. The most striking effect of this resin addition is its influence on concrete strength. While 1-year values of 5-bag or richer mixes are lower than with normal cement, the strength of the leaner mixes is higher for the treated product.

Permeability.

While regular permeability tests were not made, two types of observations have indicated that concrete containing these treated cements is more impermeable than ordinary concrete. First, when 6-in. by 12-in. cylinders have been stored in mist for 28 days or longer, their interiors always appear damp on breaking. With cements containing resin or tallow, this internal moisture is much less in evidence. A considerable number of cylinders whose surfaces had been continuously wet for five years were recently broken and revealed practically dry interiors. The second type of observation has been on thin sections of concrete. In this work it is necessary to expel all uncombined water, and then fill the resulting air spaces with a mounting resin in order to obtain clear sections for microscopic study. With normal concrete this is readily accomplished. With treated cements, however, it is often impossible to saturate the specimens with mounting resin on account of their low rate of absorption.

These observations lead to the belief that the high resistance of concrete to freezing and thawing, when the admixtures under consideration are present, is due to the influence of the resin or fat on the microstructure of the hardened paste. The capillaries in these pastes must be of considerably smaller size when the admixtures are present. It seems that, with adequate curing, highway slabs, after once becoming dry, never become resaturated when admixtures such as resins or fats are present. Since alternations of temperature above and below freezing have no effect on dry concrete (except for the stresses due to thermal volume change), the effect of frost on these special concretes is materially less than is encountered in normal mixes.

TABLE III.—EFFECT ON CONCRETE OF THE ADDITION OF RESIN TO CEMENT.
(Strengths in lb. per sq. in.).

Sacks Cu.yd.	Net W/C	Flow %	Slump In.	Wgt Cu.ft.	Voids %	Strengths 1 Da	3 Da	7 Da	28 Da	3 Mo	1 Yr
2" Slump Concrete — Moist Curing											
Cement "H"— No Admixture — 2040 Specific Surface											
3.49	9.54	159	1.9	146.4	3.1	250	1140	1820	2460	2340	2230
4.27	7.80	171	2.1	147.9	2.6	400	1820	2720	3670	3570	3540
5.05	6.21	158	2.0	149.9	2.3	730	2670	3990	4750	4940	5380
6.00	5.11	160	2.0	150.6	2.1	1180	3390	5110	5480	6120	6490
7.51	4.36	157	2.1	151.5	1.6	1870	4110	5600	6280	6950	7620
Cement "H_1"— 0.020% Vinsol Resin — 1670 Specific Surface											
3.42	8.60	151	1.9	142.4	6.8	270	890	1610	2290	2410	2560
4.22	6.90	154	2.0	145.2	5.7	420	1300	2280	3140	3420	3670
4.95	5.94	163	2.2	146.5	4.8	570	1840	2940	3960	4450	4710
5.95	5.04	159	2.0	148.8	3.5	850	2480	4000	4710	5480	6030
7.52	4.19	154	2.0	151.1	2.2	1410	3490	4600	5560	5860	6580
6" Slump Concrete — Moist Curing											
Cement "H"— No Admixture — 2040 Specific Surface											
3.46	10.69	210	5.9	146.2	2.1	170	830	1440	1830	1930	1870
4.24	8.22	200	6.0	147.6	2.2	350	1500	2370	3390	3410	3430
4.99	6.77	192	6.0	149.1	1.9	580	2200	3320	4140	4550	4720
5.95	5.64	192	6.0	150.2	1.5	930	3050	4490	4880	5580	5990
7.41	4.80	198	6.0	150.6	1.2	1580	3490	5040	5650	6170	6930
Cement "H_1"— 0.020% Vinsol Resin — 1670 Specific Surface											
3.31	9.38	198	6.2	138.6	8.8	240	740	1250	1920	2040	2130
4.11	7.23	191	6.0	141.9	7.1	370	1250	2080	3000	3180	3500
4.82	6.17	197	6.0	143.3	6.2	500	1700	2590	3700	4190	4340
5.80	5.35	181	6.0	146.0	4.8	740	2300	3470	4760	5230	5470
7.27	4.64	189	6.0	147.1	3.7	1070	2700	4140	5060	5860	6340

Conclusions.

Data from many more tests than are presented here have shown that the durability of Portland cement concrete may be improved materially by the introduction of small quantities of water-repellent materials into the cement. Workability and plasticity of fresh concrete are also improved by the additions. Bleeding, especially in the lean mix range, is reduced to a minimum by the resins or fats, but is not appreciably changed by mineral oils.

The quantity of material which may be added to Portland cement without more than moderate reductions in compressive strength or increases in air content of concrete is dependent on the character of the added material, the type of concrete mix, and to some extent the composition or other properties of the

cement to be treated. From data obtained in the Lone Star Research Laboratory, the optimum quantities are about as follows :

Mineral oils	0·04 to 0·06 per cent.
Animal fats or oils	0·01 to 0·03 per cent.
Vinsol resin	0·02 to 0·03 per cent.

In the design of concrete an increase in quantity of treated cement of 4 to 6 per cent. by weight is required to maintain a cement content equivalent to that with normal Portland cements. Decreases in concrete strength which have been obtained with the admixtures would have been less if constant cement content had been maintained.

The percentage of air content in concrete induced by resins or fats is dependent on the water-cement ratio, and also on consistency. Air content increases are least in rich mixes of stiff consistency, and greatest in lean and wet mixes.

The greatest amount of air cells in treated cement concrete is not believed to be the source of higher durability, but merely an incidental characteristic. The basic reason for greater durability apparently is the effect of the admixtures on permeability.

Shrinkage of concrete on drying has not been appreciably affected by additions of resins or mineral oil in any of many tests. Animal fats have materially increased shrinkage in all but one series. None of the admixtures tested had any influence on volume change in water storage. Since drying shrinkage is a factor in most concrete construction, the use of resins or mineral oil is much preferable to the animal fats. As the resins have greater effect than mineral oils in promoting durability, they offer the greatest potentialities for improvement in concrete.

Use of these cements in roads and structures has confirmed the laboratory findings.

Production of Iron in Portland Cement Kilns.

IN our issue for December, 1935, an account was given of the process, invented by M. Lucien Basset, in use at the works near Barcelona of the Asland Cement Company for the production of pig iron in rotary cement kilns. Before its conversion for the production of cement and iron the kiln had a capacity of 150 tons of Portland cement clinker in 24 hours; after conversion the output in 24 hours was 80 tons of Portland cement clinker and 50 tons of pig iron, both of which were of good quality.

This process is now in use in Japan by the Asano Cement Company, and was recently described by Messrs. S. Ideta and S. Hata at a meeting of the Association of Japanese Portland Cement Engineers. It appears that the Basset process has been to some extent modified by the Japanese, and is now operating in three dry-process plants. The authors state that operations under this modified

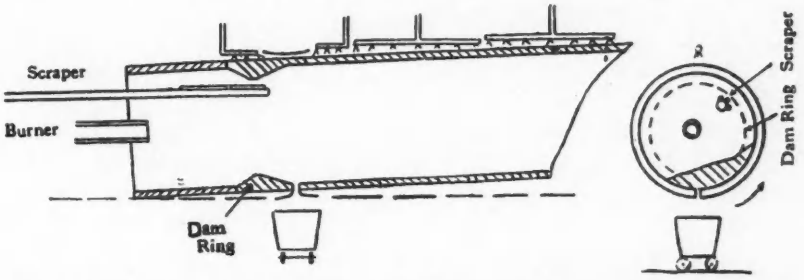


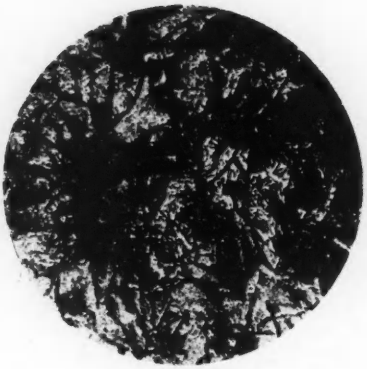
Fig. 1. Section of Rotary Kiln showing Dam and Hole through which Molten Iron Flows at Each Revolution.

process, by using a slightly higher quantity of fuel in an ordinary rotary cement kiln, produce carburised iron along with the cement clinker. As in the installation in Spain, separation of the iron from the clinker is readily accomplished, and the raw materials include iron pyrites. In both instances the process is similar to the reactions in a blast-furnace.

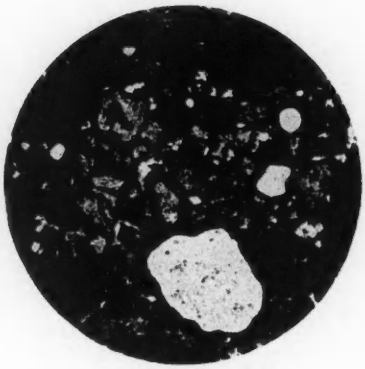
Raw materials used include limestone and coke in addition to the iron pyrites. The reactions within the kiln, as zones of higher temperature are reached, include the expulsion of combined water, expulsion of carbon dioxide, reduction of the iron ore, carburisation of the iron thus formed, and its fusion. The clinker or slag composition in the kiln, being high in lime, does not fuse completely, but reaches the normal state of incipient fusion of cement clinker.

Sections of the kiln are shown in Fig. 1. It will be seen that the kiln lining has been given an unusual shape in order to form a " dam ring " which prevents the molten iron from following the clinker out of the kiln. At the foot of the ring a permanently open discharge hole is provided in the shell of the kiln, and at each revolution of the kiln, when this hole reaches its lowest point, the molten

White Pig Iron
(x 100)



Grey Pig Iron
(x 250)



Iron Particles in Clinker
(x 100)

Fig. 2. Micrographs of Iron and Cement Clinker Produced in Rotary Kiln.

iron flows out through it and into a ladle under the kiln, which has a constant swinging movement. The molten iron is immediately moulded into pigs.

The cement clinker continues on through the kiln and is discharged into a rotary cooler. A magnetic separator is placed so as to remove the few particles of iron remaining with the clinker.

The Drying-out of Concrete in Air.

THE results of some experiments on the drying-out and strength of specimens of concrete at different sizes and at different humidities carried out by Professor H. J. Gilkey (head of the Department of Theoretical and Applied Mechanics at Iowa State College, U.S.A.) are given in *Table I.* As would be expected, the rate of drying out and the corresponding increase in strength vary inversely with the volume of the specimen and the relative humidity, and directly with the

TABLE I.—EFFECT OF RATE OF AIR DRYING ON CONCRETE SPECIMENS.

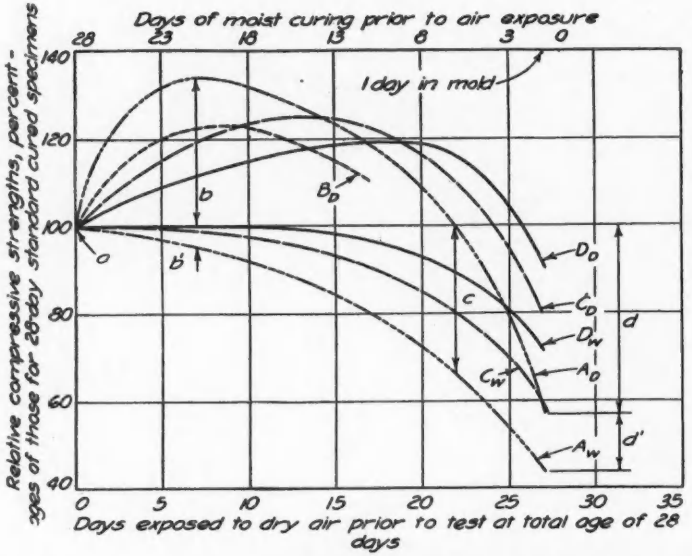
Days in Air Prior to Test	TOTAL AGE AT TEST				
	1 year		6 mo.	3 mo.	28 da.
	2x2x4 prism	3x6 cylinder	2x2x4 prism	2x2x4 prism	2x2x4 prism
0 (Std)	7060 (100)	6540 (100)	7000 (100)	6050 (100)	4675 (100)
1	--	--	7440 (107)	--	--
2	7180 (101.5)	--	7940 (114)	6900 (114)	5040 (108)
3	7440 (105.5)	--	8210 (118)	7360 (122)	5400 (116)
4	7810 (112)	--	--	7470 (123)	5330 (114)
8	8530 (121)	7900 (121)	8510 (122)	7500 (124)	5660 (121)
15	8600 (122)	7570 (116)	8400 (120)	7510 (124)	5300 (114)
22	8480 (120)	8380 (128)	--	7360 (122)	5010 (107)
29	8500 (120)	8210 (126)	--	7210 (120)	--
Period of exposure	May-July		Jan-Feb	Oct-Nov	Aug-Sept
Approx. Humidity range	60-90		10-30	10-30	60-90

[Figures in parenthesis give the strengths in percentages of specimens tested by standard methods and tested when moist.]

specific surface. The table also shows that the drying effects are essentially identical for concretes and mortars of all ages after as much as three months of moist curing. The 28-day cycle (in the last column) shows how the curing and drying effects at early ages are intermingled to produce ascending and descending ratios if the curing cycle is a short one.

In *Fig.* 1 the nature of the short cycle for various combinations of curing, drying, retarded curing, and re-soaking effects is illustrated for two sizes of

specimens exposed to two humidities of air. That the trends shown are typical has been demonstrated by many similar tests. Although the published records show that the increased strength from air-drying may be expected to become appreciable only after days rather than hours of air exposure, the fact remains that the medley of effects and counter-effects is confusing, and for that reason



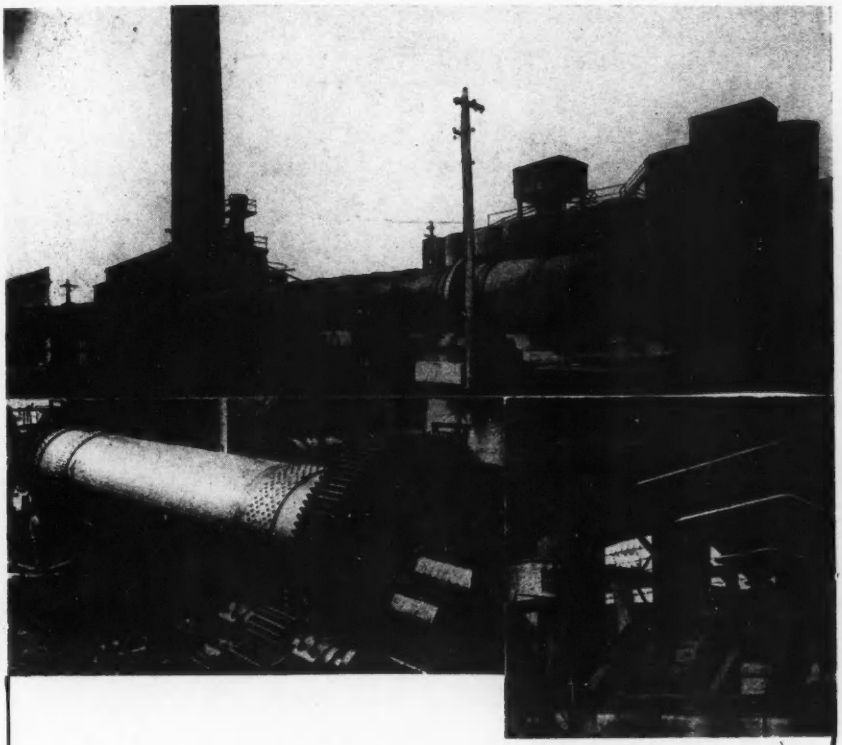
Curve	Symbol	Mixture	Size Spec	Relative Humidity Approx. Range	Values of Maximum Str. Approx. Percent	Days Moist *	Days in air	Values at 1-Day, Approx. Perct.
A (Dry)	———	Mortar	2x4-in. Cyl.	10-30	134	21	7	114
(Wet)					95			100
B (Dry)	- - - -	Mortar	2x2x4-in. Prism	60-90	122	19	9	105
(Wet)								
C (Dry)	— — —	Concrete	6x12-in.	10-30	125	15	13	103
(Wet)					95			100
D (Dry)	———	Concrete	6x12-in.	60-90	118	8	20	102
(Wet)					91			100

*Includes one day in mold.

Fig. 1. Effect of Humidity and Size of Specimen on Strength at 28 days, showing Increase in Strength due to Air Drying, and Decrease in Strength due to Retarded Curing.

the indications of *Fig* 1 are discussed in greater detail than might otherwise be warranted.

Curves A_D and A_W are from small (2 in. by 4 in.) mortar specimens for which exposures were in still but unusually dry laboratory air. The rapidity and extent of the response to air drying represents about the limit for normal indoor still-air conditions. Curve B_D is also from small specimens (2 in. by 2 in. by



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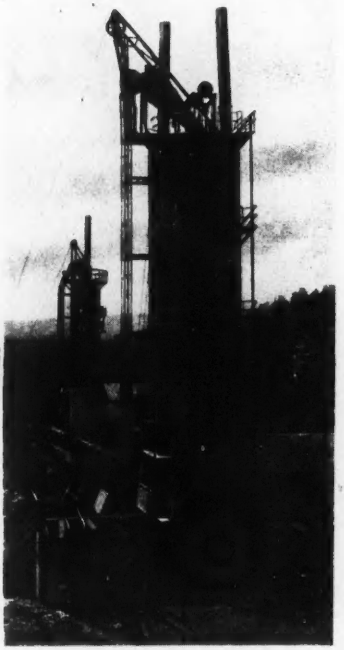

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4 in. prisms), but the exposures were in air of relatively high humidity. The humidities corresponding to *A* and *B* are repeated for the larger concrete specimens of *C* and *D*, the effect of size of specimen on rate of strength gain from drying being the important variable introduced. The *D* curve is typical of what should be expected from 6 in. by 12 in. concrete laboratory specimens anywhere in average conditions.

In *Fig.* 1 the 28-day standard-cured compressive strength is taken as the 100 per cent. datum from which all curves start at *a*. Using the A_D and A_w curves as illustrative, the maximum strength was about 134 per cent. (ordinate *b*), which was the 28-day dry-tested strength corresponding to an air exposure of seven days following 20 days immersion (after removal of the mould at one day). The corresponding wet-tested strength (if resoaked for from 12 to 24 hours prior to test) is shown on the A_w curve directly below to be about 95 per cent. The 5 per cent. reduction *b'* below that for standard-curing represents the loss from the lack of curing that occurred between the 21st and 28th day. The specimen did not lose the full seven days of curing, since it did not immediately dry out sufficiently to halt hydration or to retard it seriously.

From the summit the dry-strength curve descends to the right as the fewer days of moist curing which accompany the added days of air exposure produce lower and lower strengths. The dry-tested strength crosses the 100 per cent. axis at *c* at about 22 days air exposure after only six days moist curing. At ordinate *c* the strength reduction from restricted curing exactly equals the strength gain during 22 days of drying. The " true strength " corresponding to *c* is the wet-tested strength along curve A_w, being about 65 per cent.

The specimen at the extreme right, at *d*, has had no moist curing beyond what it got during one day in the mould and in the short period thereafter before drying out halted further hydration. The right-hand strengths are all " air-cured." The dry-tested strength of *A* is only about 56 per cent., which is reduced by resoaking to about 44 per cent. of the standard cured strength.

Apart from possible effects from differences in the mixture, curves C_D and D_D should, with the same periods of effective curing (equal amounts of drying out), rise to the same respective heights as curves A_D and B_D. During the 28-day period both the curing and the drying effects are so active that the effects of the wet or dry condition at the time of testing cannot be satisfactorily separated from curing effects. Drying effects are about the same at any age, but curing effects become almost dormant after from three to six months. Had these specimens all been moist-cured for six months or more, the ascending drying curves would be about the same as shown, except that the tops would be raised an amount about equal to the retarded curing effects shown in *Fig.* 1, at which level the curves would continue horizontally. Resoaking would lower the strengths only down to the 100 per cent. line instead of below it, because little or no retarded curing effect would be present. The data of the one-year, six-months and three-months' tests (columns 2 to 5 of the table) show the virtually constant strength

ratio of the dry concrete where variable curing effects are not present ; these are in contrast with the descending ratios of the last column.

The fallacy of attempting to draw conclusions from concrete strength tests on specimens which have not been brought to a uniform moisture condition by soaking for about a day prior to the test is apparent from *Fig.* 1. Thus the D_D curve shows at about 26 days a dry-tested strength equalling that for 28-days standard curing, whereas the only properly comparable strength is that on the D_w curve (about 76 per cent.).

The data of the table and the last column of the tabulation beneath *Fig.* 1 show that, for any but very small specimens exposed to very dry air, there will not be enough drying out in a few hours or a day to have a discernible influence upon the strength developed.

SUMMARY

In summarising, it may be reiterated that :

(a) A failure to discriminate between dry-tested strengths and wet-tested strengths may be expected to introduce comparative errors of from 20 to 40 per cent.

(b) A soaking period of from 12 to 24 hours is usually ample to bring concrete to the " wet at test " condition, which is the only proper condition for obtaining strengths which purport to represent the " true strength " of the concrete. (Resumed curing effects start slowly, and resoaking periods up to two or three days have no significant " resumed curing " effect.)

(c) An air-drying period of from one to three weeks (depending upon relative humidity and size of specimen) is necessary to develop the maximum air-dry strength.

(d) While it is always good practice and on the safe side to see that even the surface of the specimen is kept moist up to the time of testing, the fact remains that a dry exterior surface from a few hours of exposure to ordinary air may be expected to have no measurable effect upon the strength obtained. A " surface-dry " condition does not produce an " air-dry " strength.